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DOUBLE GALVANIZED STEEL STRAND AND IRON WIRE FOR ELECTRICAL TRANSMISSION AND DISTRIBUTION

INDIANA STEEL AND WIRE COMPANY
MUNCIE, INDIANA, U. S. A.

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Double Galvanized Steel Strand

and

Iron Wire

for

Electrical Transmission

and

Distribution

Indiana Steel and Wire Company
Muncie, Indiana, U. S. A.

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PREFACE

There has been widespread inquiry for information concerning the use of double galvanized iron wire and steel strand for transmission purposes.

The mechanical properties of iron wire and steel strand are well known but their electrical characteristics under various conditions have not received as much investigation.

Recognizing this fact, we have had prepared and are submitting herewith a technical report covering tests made on steel strand and iron wire to determine their electrical characteristics for power conductors.

It contains new data and information which we believe the Engineering Profession will welcome, and will find useful and helpful in considering the use of steel power conductors.

There are many cases where iron wire and strand can be, and are being successfully used in power lines, with reliability and economy.

Just when and how depends on local conditions and is purely an engineering problem but the following treatise should aid you materially in solving your own individual problems.

This booklet covers in a general way the very points that have been uppermost in the minds of Engineers and should fill a real want in the field of Transmission Line Engineering.

INDIANA STEEL AND WIRE COMPANY

March 1, 1921

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DOUBLE GALVANIZED STEEL STRAND
AND
IRON WIRE
FOR
ELECTRICAL TRANSMISSION
AND
DISTRIBUTION

INDIANA STEEL AND WIRE COMPANY
MUNCIE, INDIANA, U. S. A.

Purpose of Tests. The object of these tests was to determine the electrical properties of certain representative sizes and grades of steel strand and iron wire, with continuous currents and with sine-wave alternating currents, under a range of conditions such that the results would be applicable in designing transmission and distribution lines in which steel conductors might be employed with advantage. The results of the tests are therefore presented and summarized in form intended to furnish convenient design data.

Test Samples. The following table shows sizes and grades of galvanized steel conductors selected for test; samples were chosen and submitted by the Indiana Steel and Wire Company.

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Data on Samples Tested

Manufacturer's Designation	Number of Wires	Average Diam. of Wire (mils)	Circular Mils		Total Cross-Section (sq. in.)	Current Density at 10 Amperes (amp. per sq. in.)
			Per Wire	Total Conductor		
⅜ in. "High Strength Strand"	7	119.5	14,280	99,960	0.07851	127.4
½ in. "Siemens-Martin Strand"	7	159.3	25,380	177,600	0.1395	71.67
⅜ in. "Siemens-Martin Strand"	7	119.5	14,280	99,960	0.07851	127.4
¼ in. "Siemens Martin Strand"	7	81.85	6,700	46,900	0.03683	271.5
⅜ in. "Standard Strand"	7	125.0	15,630	109,400	0.08590	116.4
No. 8 B. W. G. "3-Ply Twisted Guy Wire"	3	162.2	26,310	78,930	0.06199	161.3
No. 6 B. W. G. "B. B. Tel. & Tel. Wire"	1	202.0	40,800	40,800	0.03205	312.0

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Results Sought. The tests were arranged to determine the following properties of the samples submitted.

1. Continuous-current resistance and resistivity.
2. Temperature coefficient of resistance.
3. Alternating-current resistance at 25 and 60 cycles.
4. Alternating-current inductance at 25 and 60 cycles.

Test Methods. The tests were conducted at the Electrical Testing Laboratories of New York City and are described in detail in their report No. 24,439 rendered to the undersigned, copy of which is submitted herewith. The following brief description is extracted from their report.

"The object of the test was to determine the alternating current resistance and the internal inductance of the various samples of wire when traversed by sine-wave alternating current at frequencies of 25 and 60 cycles per second. The temperature rise of the wires under these conditions was noted. Measurements were also made of the resistivity and the resistance temperature coefficient.

"Briefly stated, the alternating current measurements were made by a Wheatstone bridge method, the wire being suspended in air in the form of a long narrow rectangular loop of constant and known dimensions. The resistance and total inductance of this loop were determined in terms of known standard resistors and inductors.

"The average length of the test loops was approximately 115 feet and the width 30 inches, the wire being supported in a horizontal plane by means of wooden spacers with "V" notches to give constant spacing. The loop was broken at the center for the introduction of current, the ends of the wire dipping in pools of mercury which were connected to the bridge net work.

"In all measurements, four observations of inductance and two of resistance were made, the inductance

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being observed with direct and reversed current in the bridge and with direct and reversed current, for each of these two conditions, through the inductance. . . . Provision was also made to throw the testing circuit on to direct current immediately upon the completion of the observations with alternating current. . . . . .The various values of alternating current were maintained until the resistance of the loop had attained final value. . . . . The measurements with alternating current were all made with current having a sine wave shape. .

"In order to check the accuracy of the results obtained, a loop composed of No. 8 copper wire was strung and measured in the same manner as the iron wire loops. The measured value of inductance obtained in this measurement showed satisfactory agreement with that obtained by computation, indicating that correct results had been obtained in inductance measurements. The measured a. c. resistance of this copper loop was identical with its measured d. c. resistance, indicating that there were no additional power losses in neighboring floor beams, columns, etc.

"In making the resistivity and resistance temperature coefficient determinations, a wire from each of the seven samples was stretched in a bath of oil, the temperature of which could be readily varied. The resistance of known lengths of these specimens were measured at various temperatures and from these values and the diameter of the wire, both resistivity and resistance temperature coefficients were computed.

"In making the computations, the observed data were first corrected for the resistance and inductance of the copper leads. The corrected loop resistance was then adjusted for the difference between the observed air temperature and 20 degrees C., using the resistance temperature coefficient obtained in the measurement described above. The external inductance of each of the loops was then computed from the measured dimensions of the wire and the loop, using the standard equation for the inductance of a rectangle taking care to exclude

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the expression representing the internal inductance of a non-magnetic wire (Bureau of Standards, Vol. VIII., No. 1, p. 155). The difference between this value and the measured inductance gave the internal inductance of the sample."

Properties with Continuous Currents

Resistivity. The values of resistivity given in the following table are stated in microhm-inch (millionths of an ohm between opposite parallel faces of a one-inch cube) and in ohms per mil-foot (round wire one foot long and one mil in diameter) at 20 degrees Centigrade. For convenience the ratios of the several resistivities to the International Annealed Copper Standard are also stated, and the ratios of the conductivities.

Resistance. The resistances of the several conductors are stated in the table in ohms per 1,000 ft. and per mile at 20 degrees Centigrade. These values are computed values based on the measured resistivity and cross-section of each sample.

Temperature Coefficient. The values for the temperature coefficient given in the table (following) express the change in resistance per degree Centigrade, from and at a reference temperature of 20 degrees Centigrade (68 degrees Fahrenheit). The values of the coefficient were computed from observed values of resistance at 20 degrees and 90 degrees Centigrade.

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Properties with Continuous Currents

Manufacturer's Designation	Total Circular Mils in Conductor	Volume Resistivity at 20 Deg. Cent.		Ratio of Resistivity to International Annealed Copper Standard	Ratio of Conductivity to International Annealed Copper Standard	Resistance at 20 Deg. Cent.		Resistance Temperature Coefficient per Deg. Cent. From and At 20 Deg. Cent.
		Microhm Inch	*Mil-foot			Ohms per 1000 ft.	Ohms per Mile	
⅜ in. "High Strength Strand"	99,960	7.02	107.3	10.34	9.67%	1.07	5.67	0.00338
½ in. "Siemens-Martin Strand"	177,600	7.38	112.8	10.87	9.20%	0.635	3.35	0.00333
⅜ in. "Siemens-Martin Strand"	99,960	6.81	104.1	10.03	9.97%	1.04	5.50	0.00348
¼ in. "Siemens-Martin Strand"	46,900	7.065	108.0	10.41	9.61%	2.30	12.2	0.00309
⅜ in. "Standard Strand"	109,400	4.57	69.8	6.73	14.85%	0.638	3.37	0.00570
No. 8 B.W.G. "3-Ply Twisted Guy Wire"	78,930	5.20	79.5	7.66	13.05%	1.01	5.32	0.00445
No. 6 B.W.G. "B. B. Tel. & Tel. Wire"	40,800	4.47	68.3	6.59	15.18%	1.67	8.84	0.00496

*Note: 1 ohm (mil-ft.)=15.28 microhm-inch. The International Annealed Copper Standard=10.37 ohms (mil-ft.) at 20 deg. Cent.

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Variations in Resistivity. With such metals as commercially pure copper and aluminum, in which all foreign elements or impurities can be reduced to a small fraction of one per cent, it is possible to standardize values of electrical resistivity with high precision, but with commercial iron and steel the case is different. The latter metals, by reason of a higher proportion of impurities due to less refined methods of manufacture and also, in the case of steel, by reason of certain proportions of other elements such as carbon, manganese, silicon, etc., are necessarily more complex in structure and under less perfect control as to composition. Hence the electrical resistivity of commercial grades of iron and steel wire should be stated in terms of averages, with certain maximum values or tolerance limits within which all (or all but a few per cent) of the material of a specified quality should conform.

The foregoing values of resistance (given in the table just preceding) check reasonably well with the measured resistance with continuous current (5 amp.) of each full sample of strand, as given later, the average difference being 2.2% with a minimum of zero and a maximum of 6.7%. These differences do not seem to be abnormal.

Properties with Sine-Wave Alternating Currents

Skin-Effect. The effective resistance of a conductor when traversed by an alternating current is greater than the ohmic or real resistance with continuous current, the ratio of the former to the latter being termed the skin-effect resistance ratio. Simultaneously with increase of resistance with alternating currents, there is a decrease of internal inductance, or that portion of the total inductance of the circuit which corresponds to the magnetic flux within the substance of the conductor; the ratio of the effective alternating-current internal inductance to the true internal inductance is termed the skin-effect inductance ratio. The magnitude of the skin-effect depends upon the following

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factors: size of conductor, contour of cross-section, character of lay if stranded, resistivity, frequency and wave form of the current and magnetic properties of the conductor material.

Primarily the cause of skin-effect is the lack of full penetration of the current throughout the cross-section of the conductor, being least, in the case of circular cross-section, at the center and maximum at the circumference. Lack of full penetration occurs because the internal reactance of the conductor is not uniform over its entire cross-section, but ranges from maximum at the center to minimum at the circumference, as the result of corresponding variation in the inductance. In general the skin-effect becomes greater with increasing diameter of conductor and with increasing frequency, but decreases with increasing resistivity. With magnetic materials having high permeability it is also much larger than with materials of low permeability or with non-ferrous materials having substantially unit permeability.

Wires of iron and steel, besides possessing magnetic permeability in varying degree, are subject to hysteresis, thus introducing another source of energy loss, not as important as the impairment of penetration, but contributing its quota to the resultant skin-effect. Spiral stranding of the conductor, as in concentric-lay or rope-lay cables, introduces still another element of loss termed the spirality effect, which is much more marked in iron and steel cables than in similar cables of non-magnetic materials.

The resultant skin-effect for non-magnetic power conductors of the usual types and sizes can be calculated or predetermined with rather close precision, but in the case of iron and steel conductors this becomes very difficult if not impracticable. Experimental results therefore become essential to the establishment of reliable design data for iron and steel conductors and are conveniently stated in terms of the skin-effect resistance ratio at various frequencies and current densities and

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in terms of the ratio of the effective internal inductance to the true internal inductance of an identical form of conductor having unit permeability. The results of the tests herein reported are expressed in the foregoing terms, in addition to stating the effective resistance and internal inductance per 1,000 feet and per mile of conductor.

Formulas For Inductance. The following formulas express the true inductance of a uniform linear conductor, with parallel return, in millihenrys per mile of conductor.

(a) Solid round wire:

$$L = 0.7411 \log_{10} \frac{d}{r} + 0.0805\mu \qquad (1)$$

(b) 3-Ply strand:

$$L = 0.7411 \log_{10} \frac{d}{r} + 0.1252\mu \qquad (2)$$

(c) 7-Wire strand:

$$L = 0.7411 \log_{10} \frac{d}{r} + 0.1033\mu \qquad (3)$$

The symbol d stands for the perpendicular separation of the conductor from its parallel return conductor (center to center) and r represents the radius of the wire or the circumscribing circle of the strand, both expressed in the same units. These formulas apply when the ratio d/r is large, as in ordinary overhead circuits of open wire, but should never be used if d/r is small, as in multiple-conductor cables. The logarithmic portion of each formula, which is the same in every case, represents the external inductance or that portion due to the magnetic flux which is wholly outside of the conductor itself. The symbol μ stands for the magnetic permeability of the conductor, here assumed for

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simplicity's sake to be constant throughout the cross-section and uniform at all current densities, but in reality a variable. The constant portion of each formula, containing the factor μ, represents the internal inductance or that portion due to the magnetic flux which is wholly inside of the conductor itself. These formulas are strictly applicable to non-magnetic conductors of unit permeability, such as copper and aluminum, but as applied to iron and steel conductors the value of μ which gives a correct result when substituted in the formula is merely an average or equivalent single value which in reality is the ratio of the internal inductance of the iron or steel conductor to the corresponding inductance of a non-magnetic conductor with zero skin-effect. The latter significance should be attached to any equivalent values of μ for iron or steel conductors computed from the results of the tests hereafter shown.

Internal Inductance Ratio. Since the internal inductance and reactance of wires and cables having unit permeability are readily calculated, it becomes convenient in the case of iron and steel conductors to have the ratio of their effective internal inductance with alternating currents to the true internal inductance of similar conductors having unit permeability. This ratio has been computed and stated for each case shown in the tabular summary of results which follows.

Power Losses. The usual expression I^2r representing the power loss in watts in a conductor of resistance r ohms traversed by a current of I amperes will apply in the present case, but with continuous currents the real or ohmic resistance should be used in the formula, whereas with alternating currents the effective or apparent (A.C.) resistance should be used.

Tabular Summary of Results. The following tables show the results of the tests upon the seven samples before mentioned, with continuous current and with sine-wave alternating current, at five different current strengths and with frequencies of 25 and 60 cycles.

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Each value of resistance given in the tables corresponds to the final temperature which the conductor would reach, with the stated value of current, when the air temperature is 20 degrees Centigrade; that is to say, each value of resistance includes the heating effect in the conductor under the condition of an air temperature of 20 degrees Centigrade. The temperature rise in each instance is stated in a subsequent table. Attention is called in particular to the skin-effect resistance ratios and the internal inductance ratios.

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⅜-in. High Strength Steel Strand
(Single Conductor)

Current in Amperes	True (D. C.) Resistance in Ohms per 1000 ft.	Effective (A. C.) Resistance		Skin Effect Resistance Ratio	True Internal Inductance at Unit Permeability in Millihenrys per 1000 ft.	Effective Internal Inductance		Internal Inductance Ratio
		Ohms per 1000 ft.	Ohms per Mile			Millihenrys per 1000 ft.	Millihenrys per Mile	
60 CYCLES								
5	1.106	1.112	5.871	1.006	0.01956	0.2565	1.354	13.11
10	1.106	1.116	5.892	1.007	0.01956	0.269	1.420	13.75
15	1.112	1.124	5.935	1.011	0.01956	0.2795	1.476	14.29
20	1.118	1.132	5.977	1.013	0.01956	0.292	1.542	14.91
25	1.124	1.142	6.030	1.016	0.01956	0.305	1.610	15.59
25 CYCLES								
5	1.102	1.105	5.834	1.002	0.01956	0.258	1.362	13.19
10	1.105	1.106	5.840	1.001	0.01956	0.270	1.426	13.80
15	1.109	1.110	5.861	1.001	0.01956	0.283	1.494	14.47
20	1.121	1.124	5.935	1.003	0.01956	0.296	1.563	15.13
25	1.129	1.135	5.993	1.005	0.01956	0.3115	1.645	15.92

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½-in. Siemens-Martin Steel Strand

(Single Conductor)

Current in Amperes	True (D. C.) Resistance in Ohms per 1000 ft.	Effective (A. C.) Resistance		Skin Effect Resistance Ratio	True Internal Inductance at Unit Permeability in Millihenrys per 1000 ft.	Effective Internal Inductance		Internal Inductance Ratio
		Ohms per 1000 ft.	Ohms per Mile			Millihenrys per 1000 ft.	Millihenrys per Mile	
60 CYCLES								
5	0.637	0.644	3.400	1.012	0.01956	0.269	1.420	13.75
10	0.639	0.648	3.421	1.014	0.01956	0.2805	1.481	14.34
15	0.640	0.649	3.427	1.015	0.01956	0.288	1.521	14.72
20	0.642	0.652	3.443	1.019	0.01956	0.296	1.563	15.13
25	0.644	0.658	3.474	1.021	0.01956	0.3085	1.629	15.77
25 CYCLES								
5	0.636	0.639	3.374	1.004	0.01956	0.2785	1.470	14.24
10	0.637	0.640	3.379	1.005	0.01956	0.283	1.494	14.47
15	0.639	0.642	3.390	1.006	0.01956	0.294	1.552	15.03
20	0.640	0.644	3.400	1.007	0.01956	0.3035	1.602	15.51
25	0.642	0.646	3.411	1.007	0.01956	0.314	1.658	16.05

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⅜-in. Siemens-Martin Steel Strand

(Single Conductor)

Current in Amperes	True (D. C.) Resistance in Ohms per 1000 ft.	Effective (A. C.) Resistance		Skin Effect Resistance Ratio	True Internal Inductance at Unit Permeability in Millihenrys per 1000 ft.	Effective Internal Inductance		Internal Inductance Ratio
		Ohms per 1000 ft.	Ohms per Mile			Millihenrys per 1000 ft.	Millihenrys per Mile	
60 CYCLES								
5	1.022	1.031	5.444	1.008	0.01956	0.265	1.399	13.55
10	1.025	1.035	5.465	1.009	0.01956	0.282	1.489	14.41
15	1.030	1.040	5.491	1.011	0.01956	0.2985	1.576	15.26
20	1.035	1.051	5.549	1.016	0.01956	0.313	1.653	16.00
25	1.046	1.065	5.623	1.017	0.01956	0.327	1.727	16.71
25 CYCLES								
5	1.024	1.027	5.423	1.002	0.01956	0.2645	1.397	13.52
10	1.027	1.029	5.433	1.003	0.01956	0.284	1.500	14.52
15	1.033	1.036	5.470	1.004	0.01956	0.300	1.584	15.33
20	1.039	1.044	5.512	1.005	0.01956	0.315	1.663	16.10
25	1.048	1.054	5.565	1.006	0.01956	0.328	1.732	16.77

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¼-in. Siemens-Martin Steel Strand

(Single Conductor)

Current in Amperes	True (D. C.) Resistance in Ohms per 1000 ft.	Effective (A. C.) Resistance		Skin Effect Resistance Ratio	True Internal Inductance at Unit Permeability in Millihenrys per 1000 ft.	Effective Internal Inductance		Internal Inductance Ratio
		Ohms per 1000 ft.	Ohms per Mile			Millihenrys per 1000 ft.	Millihenrys per Mile	
60 CYCLES								
5	2.315	2.32	12.25	1.002	0.01956	0.2765	1.460	14.13
10	2.335	2.345	12.38	1.003	0.01956	0.2895	1.529	14.80
15	2.36	2.375	12.54	1.006	0.01956	0.312	1.647	15.95
20	2.40	2.415	12.75	1.008	0.01956	0.326	1.721	16.66
25	2.445	2.47	13.04	1.009	0.01956	0.3505	1.851	17.92
25 CYCLES								
5	2.305	2.31	12.20	1.001	0.01956	0.278	1.468	14.21
10	2.33	2.33	12.30	1.001	0.01956	0.292	1.542	14.92
15	2.365	2.37	12.51	1.002	0.01956	0.3115	1.645	15.92
20	2.405	2.41	12.72	1.003	0.01956	0.328	1.732	16.77
25	2.450	2.465	13.02	1.006	0.01956	0.356	1.880	18.20

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⅜-in. Standard Steel Strand

(Single Conductor)

Current in Amperes	True (D. C.) Resistance in Ohms per 1000 ft.	Effective (A. C.) Resistance		Skin Effect Resistance Ratio	True Internal Inductance at Unit Permeability in Millihenrys per 1000 ft.	Effective Internal Inductance		Internal Inductance Ratio
		Ohms per 1000 ft.	Ohms per Mile			Millihenrys per 1000 ft.	Millihenrys per Mile	
60 CYCLES								
5	0.686	0.741	3.912	1.080	0.01956	0.614	3.242	31.38
10	0.686	0.771	4.071	1.130	0.01956	0.743	3.923	37.98
15	0.686	0.827	4.367	1.207	0.01956	0.889	4.694	45.44
20	0.696	0.943	4.979	1.346	0.01956	1.067	5.634	54.54
25	0.707	1.067	5.634	1.512	0.01956	1.198	6.325	61.23
25 CYCLES								
5	0.681	0.707	3.733	1.036	0.01956	0.738	3.897	37.72
10	0.684	0.728	3.844	1.064	0.01956	0.932	4.921	47.64
15	0.690	0.771	4.071	1.117	0.01956	1.172	6.188	59.90
20	0.698	0.830	4.382	1.191	0.01956	1.433	7.566	73.25
25	0.700	0.875	4.620	1.250	0.01956	1.618	8.543	82.70

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3-Ply No. 8 B. W. G. Twisted Guy Wire

(Single Conductor)

Current in Amperes	True (D. C.) Resistance in Ohms per 1000 ft.	Effective (A. C.) Resistance		Skin Effect Resistance Ratio	True Internal Inductance at Unit Permeability in Millihenrys per 1000 ft.	Effective Internal Inductance		Internal Inductance Ratio
		Ohms per 1000 ft.	Ohms per Mile			Millihenrys per 1000 ft.	Millihenrys per Mile	
60 CYCLES								
5	1.026	1.086	5.734	1.059	0.02371	0.751	3.965	31.67
10	1.030	1.134	5.987	1.102	0.02371	0.951	5.020	40.11
15	1.036	1.217	6.426	1.179	0.02371	1.198	6.325	50.52
20	1.052	1.343	7.091	1.275	0.02371	1.476	7.793	62.25
25	1.067	1.435	7.577	1.345	0.02371	1.706	9.008	71.95
25 CYCLES								
5	1.024	1.044	5.512	1.018	0.02371	0.745	3.934	31.42
10	1.028	1.063	5.613	1.034	0.02371	0.951	5.020	40.11
15	1.040	1.115	5.887	1.073	0.02371	1.286	6.790	54.24
20	1.045	1.205	6.362	1.152	0.02371	1.649	8.707	69.54
25	1.062	1.270	6.706	1.195	0.02371	2.045	10.80	86.24

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No. 6 B. W. G. "B. B." Telephone and Telegraph Wire

(Single Conductor)

Current in Amperes	True (D. C.) Resistance in Ohms per 1000 ft.	Effective (A. C.) Resistance		Skin Effect Resistance Ratio	True Internal Inductance at Unit Permeability in Millihenrys per 1000 ft.	Effective Internal Inductance		Internal Inductance Ratio
		Ohms per 1000 ft.	Ohms per Mile			Millihenrys per 1000 ft.	Millihenrys per Mile	
60 CYCLES								
5	1.67	2.54	13.41	1.525	0.01525	3.585	18.93	235.1
10	1.675	3.26	17.21	1.950	0.01525	4.035	21.30	264.7
15	1.695	3.375	17.82	1.990	0.01525	4.125	21.78	270.6
20	1.75	3.325	17.56	1.900	0.01525	4.10	21.65	268.9
25	1.84	3.22	17.00	1.760	0.01525	3.92	20.70	257.1
25 CYCLES								
5	1.67	2.14	11.30	1.281	0.01525	4.735	25.00	310.6
10	1.695	2.55	13.46	1.508	0.01525	6.555	34.61	429.9
15	1.72	2.57	13.57	1.494	0.01525	6.675	35.24	437.8
20	1.755	2.515	13.28	1.433	0.01525	6.595	34.82	432.6
25	1.82	2.495	13.17	1.373	0.01525	6.45	34.06	423.1

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Temperature Rise. In making the tests the various values of alternating current were maintained until the resistance of the loop had attained final value. The observed rise of temperature of each sample above air temperature (20 deg. Cent.) is given for each test in the accompanying table.

Temperature Rise Above Air Temperature
(Deg. Cent.)

	Test Frequency	Current in Amperes				
		5	10	15	20	25
3/8-in. High Strength Strand	60	0.2	0.6	1.8	3.0	4.6
	25	0.2	0.8	1.6	....	....
1/2-in. Siemens-Martin Strand	60	0.2	0.8	1.2	1.8	2.8
	25	0.2	0.8	1.2	1.8	3.0
3/8-in. Siemens-Martin Strand	60	0.4	1 4	2.4	4.6	6.6
	25	0.4	1.6	3.0	4.4	6.4
1/4-in. Siemens-Martin Strand	60	0.6	2.8	5.4	11.8	17.8
	25	0.6	3.2	7.4	12.6	18.2
3/8-in. Standard Strand	60	0.2	1.0	2.0	2.6	5.0
	25	0.2	1.2	2.0	3.0	5.6
3-Ply No. 8 B.W.G. Twisted Guy Wire	60	0.2	1.0	2.6	5.8	9.2
	25	0.2	1.0	3.6	5.4	8.6
No. 6 B.W.G. "BB" Tel. Wire	60	0.2	2.8	7.4	13.2	22.8
	25	0.2	2.6	6.6	10.6	18.4

Curves of Effective Resistance and Internal Reactance for each of the seven samples, per 1,000 feet of single conductor, at 25 and 60 cycles, will be found at the end of this report. It should be kept in mind that these curves show the characteristics of but one sample in

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each case and are not average results determined from a comprehensive series of tests intended to be completely representative of each class or grade as a whole. But there is no reason to doubt that each sample, within reasonable tolerance limits, is characteristic of its class.

Tables of Effective Resistance, Internal Reactance and Line Loss for each of the seven samples, per mile of conductor, will be found at the end of the report supplementing the curves before mentioned.

Comparison of Results

Comparisons Among Three Different Grades of Strand of Equal Size. The three strands of ⅜-in. "High Strength", "Siemens-Martin" and "Standard" grades afford a basis of direct comparison at equal current densities, as shown in the next table.

Comparisons Among Three Different Grades of ⅜-in. Steel Strand

Currrent in Amperes	Skin Effect Resistance Ratio			Internal Inductance Ratio		
	High Strength Strand	Siemans-Martin Strand	Standard Strand	High Strength Strand	Siemens-Martin Strand	Standard Strand
60 CYCLES						
5	1.006	1.008	1.080	13.11	13.55	31.38
10	1.007	1.009	1.130	13.75	14.41	37.98
15	1.011	1.011	1.207	14.29	15.26	45.44
20	1.013	1.016	1.346	14.91	16.00	54.54
25	1.016	1.017	1.512	15.59	16.71	61.23
25 CYCLES						
5	1.002	1.002	1.036	13.19	13.52	37.72
10	1.001	1.003	1.064	13.80	14.52	47.64
15	1.001	1.004	1.117	14.47	15.33	59.90
20	1.003	1.005	1.191	15.13	16.10	73.25
25	1.005	1.006	1.250	15.92	16.77	82.70

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The foregoing comparisons show that the skin-effect resistance ratios in the "High Strength" and "Siemens-Martin" samples are of a nominal order and increase but slightly with the current density; the internal inductance ratios are also of relatively small magnitude and consistent with the low values of skin-effect resistance ratio. These samples evidently have low magnetic permeability characteristic of medium hard steel. The sample of "Standard" grade exhibits pronounced skin effect increasing rapidly with increase of current density and much higher internal inductance ratios, implying that the steel is considerably softer than the other two samples. These results as a whole are consistent with the respective values of conductivity (D.C.) which are approximately 10% of the International Annealed Copper Standard for "High Strength" and "Siemens-Martin" and 15% for "Standard".

Owing to the differences above mentioned, it becomes a question in any practical case as to which grade of steel should be selected in order to obtain the smallest permissible conductor from the electrical standpoint. This will be made clearer by the next table comparing the actual effective resistances of these three samples.

Effective (A. C.) Resistance of ⅜-in. Steel Strand—Ohms Per Mile

Current in Amperes	60 CYCLES			25 CYCLES		
	High Strength Strand	Siemens-Martin Strand	Standard Strand	High Strength Strand	Siemens-Martin Strand	Standard Strand
5	5.871	5.444	3.912	5.834	5.423	3.733
10	5.892	5.465	4.071	5.840	5.433	3.844
15	5.935	5.491	4.367	5.861	5.470	4.071
20	5.977	5.549	4.979	5.935	5.512	4.382
25	6.030	5.623	5.634	5.993	5.565	4.620

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It appears from the comparisons in the last table that the "Standard" sample will have lower effective (A.C.) resistance at 60 cycles, up to 25 amperes, but for larger currents it is probable that the "Siemens-Martin" sample will have the lower resistance; at 25 cycles the "Standard" sample has in every case lower resistance than the "Siemens-Martin", although the two show a tendency to approach the same resistance at some larger value of current. In every case the internal reactance of the "Standard" sample is several times larger than that of the other two.

Comparisons Among Three Different Sizes of Siemens-Martin Strand exhibit fairly consistent results. The skin-effect resistance ratio, while nominal in value, increases slightly with increasing current and also increases slightly with increasing diameter of strand, but decreases with lower frequency. The internal inductance ratio shows a slight but consistent increase with increasing current; as a whole it also shows a very slight increase at the lower frequency and a slight tendency to increase with decreasing diameter of strand, which corresponds, at the same current value, to increasing current density. The main characteristics of these three samples of "Siemens-Martin" strand are: (a) nominal skin effect; (b) relatively low internal inductance ratio; (c) neither skin-effect nor inductance ratio are very materially affected by changes in frequency (below 60 cycles) and current density.

Comparisons Among Standard Strand, Guy Wire and B.B. Wire disclose certain characteristic differences, particularly noticeable in the case of the sample last mentioned. The comparisons set up in the next table are based on equal currents and consequently, because of differences in cross-section, do not represent equal current densities; for equal values of current the density is least in the "Standard Strand", intermediate in the "Guy Wire" and highest in the "B.B." wire.

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Comparisons Among Standard Strand, Guy Wire and "B. B." Wire

Current in Amperes	Skin Effect Resistance Ratio			Internal Inductance Ratio		
	3/8-in. Standard Strand	3-Ply No 8 Guy Wire	No. 6 "B.B." Wire	3/8-in. Standard Strand	3-Ply No. 8 Guy Wire	No. 6 "B.B." Wire
60 CYCLES						
5	1.080	1.059	1.525	31.38	31.67	235.1
10	1.130	1.102	1.950	37.98	40.11	264.7
15	1.207	1.179	1.990	45.44	50.52	270.6
20	1.346	1.275	1.900	54.54	62.25	268.9
25	1.512	1.345	1.760	61.23	71.95	257.1
25 CYCLES						
5	1.036	1.018	1.281	37.72	31.42	310.6
10	1.064	1.034	1.508	47.64	40.11	429.9
15	1.117	1.073	1.494	59.90	54.24	437.8
20	1.191	1.152	1.433	73.25	69.54	432.6
25	1.250	1.195	1.373	82.70	86.24	423.1

The skin-effect resistance ratio, making allowance for differences in density at equal values of current, is least in the "Guy Wire" and maximum in the "B.B." wire. The same relations hold true for the internal inductance ratio, thus indicating that the "Guy Wire" is the hardest sample of the three, "Standard Strand" being intermediate and "B.B." wire the softest. Besides having much the highest skin-effect resistance ratio of all the samples, the "B.B." wire also has by far the largest internal reactance. A further effect noted only in the "B.B." sample is the decrease of skin-effect resistance ratio and internal inductance ratio after the current exceeds approximately 15 amperes, which cor-

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responds to the characteristic maximum point or hump in the flux-permeability curve of soft iron or soft steel. Possibly the same effect would be noted in the case of the "Standard Strand" or the "Guy Wire" sample if the current density were increased to considerably greater values.

While there might be some question, in a particular case, whether "Guy Wire" or "Standard Strand" would be the better choice as between the two, it is fairly evident that both are superior to "B.B." wire, at least so far as these tests show. By applying skin-effect resistance factors to the values of volume resistivity given earlier in this report, it will also be seen that "B.B." wire at 60 cycles is probably inferior to "Siemens-Martin" steel at equal current densities; at 25 cycles the reverse is probably true.

Wave Distortion. In the tests on the smaller wires it was noted that wave distortion was produced and this was severest with the No. 6 "B.B." sample. The reason for such distortion is the varying permeability of the steel or iron with changes in current strength from instant to instant, which in turn causes corresponding changes in the instantaneous values of internal inductance and internal reactance. Such pulsation of the internal reactance is sufficient in itself to cause wave distortion, but its effect as a whole is augmented by the fact that it causes corresponding pulsation of the effective (A.C.) resistance. Current of sine-wave shape was maintained in each sample throughout the tests, with the result that distortion occurred in the potential wave of impedance drop across the terminals of the test loop. Suitable means were adopted in the tests to eliminate the effects of any such distortion upon the results.

Wave distortion is objectionable *per se*, because it tends to increase the losses in any alternating current system and impair the efficiency. While no specific investigation of wave distortion has been made in connection with these tests, it is proper to point out that

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such distortion will always occur in some degree with iron and steel conductors, being most pronounced with wires of high permeability and vice versa. This constitutes an objection to the use of that class of alternating current conductors of which the No. 6 "B.B." wire is generally typical, although the objection is not necessarily conclusive. The corresponding advantage in the use of the harder grades of material, such as "Siemens-Martin", or "High Strength" is self-evident. With the latter materials the skin-effect resistance ratio and the internal inductance ratio are both so nominal in value that the resultant wave distortion is probably insignificant from a commercial standpoint.

Commercial Application

Line Resistance, Reactance and Impedance per 1,000 feet or per mile of single conductor at 25 or 60 cycles with any particular spacing or arrangement of conductors may be determined from the data previously given, according to well known methods. In order to facilitate rapid determination of the total effective reactance, the following rule will sometimes be convenient for making use of reactance tables for copper conductors: determine from such a table the reactance of a copper conductor of the same size as the steel conductor under consideration, at the given frequency and conductor spacing; subtract from the total reactance thus found the internal reactance (given below) and add to the remainder the effective internal reactance of the steel conductor under the stated conditions as to frequency and current density, which will give the total reactance desired. When not convenient to make use of tables, the total reactance for steel may be found by computing the external reactance from the inductance formulas previously given and adding to this result the proper value of internal reactance for the stated conditions. The internal reactances of copper conductors in ohms per mile, neglecting skin effect, are as follows:

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	60 CYCLES	25 CYCLES
Solid Wire	0.030	0.013
3-Ply Strand	0.047	0.020
7-Wire Cable	0.039	0.016

Line Drop and Loss are computed by well known methods which may be found in various standard textbooks and handbooks. Particular care should be taken in the case of iron and steel conductors, however, to use the effective values of resistance and reactance which would exist under the stated condition of frequency and current density.

Current Carrying Capacity of any conductor is limited by that value of I^2r or energy loss which raises its temperature to the safe maximum limit. This capacity being well defined for copper conductors (National Electrical Code Rules), it is possible to make an approximate rule for iron and steel conductors which will in general be a safe guide. The rule may be stated as follows: Divide the conductivity (D.C.) ratio of steel to copper by the skin-effect resistance ratio, find the square root of the result and multiply this figure by the current-carrying capacity of a copper conductor of the same size as the steel conductor under consideration, which will give the desired approximate carrying capacity of the steel conductor. Example: the conductivity ratio of a certain No. 6 B. W. G. steel wire is 10 per cent and its skin-effect resistance ratio at about 25 amp. is 1.12; the quotient of $0.100 \div 1.12$ is 0.0893 and the square root of 0.0893 is 0.299; the nearest A. W. G. size of copper wire is No. 4, which has a carrying capacity of 90 amp.; the product of 90×0.299 is substantially 27 amp., which is the approximate carrying capacity of this No. 6 steel wire for the same temperature rise permissible with copper wire of equal size.

Example of Applicability of Steel Cable to High-Tension Transmission. Given a 20-mile, 3-phase, 110,000

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volt, 60 cycle line delivering 5,000 kva at 80% power factor, with permissible line drop not exceeding 10% and a conductor spacing of 10 ft. Consideration of the factor of corona discharge at once fixes the minimum permissible cable diameter at approximately 0.43 in., provided the line is situated at sea level and the temperature does not exceed 25 deg. Cent. or 77 deg. Fahr. Let it be assumed that because of elevation and temperature a 0.5-in. cable must be used. As a first approximation assume that the line drop will be the full 10% allowed; it follows that the load current at the receiver will be 29.2 amp. per phase wire. A 0.5-in. Siemens-Martin cable, at 25 amp., will have an effective resistance of 3.47 ohms per mile and an internal reactance of 0.614 ohm per mile; the external reactance will be 0.749 ohm, making a total reactance of 1.36 ohms per mile. Taking slightly higher values of resistance and reactance, say 3.5 ohms and 1.40 ohms respectively, and computing the total line drop upon the assumption that the line charging current can be neglected, it appears that the drop will be approximately 3%. The line charging current, computed upon the assumption of constant line pressure from end to end, will be 6.9 amp. per phase wire, or roughly one-fourth of the load current. It is evident without further consideration that the 0.5-in. Siemens-Martin cable will more than satisfy the requirements as to voltage regulation.

Second Example. Given a 10-mile, 3-phase, 33,000 volt, 60 cycle line delivering 500 kva at 85% power factor, with a line loss not exceeding 10% of the power delivered to the line; conductor spacing, 36 in. Delivery of 500 kva at 33,000 volts will require approximately 8.8 amp. per phase wire, but on account of the line drop, which will reduce the voltage at the receiver, it may be assumed that the actual current will be about 9.5 amp. The delivered energy is 425 kw, representing 90% of the total energy delivered to the line, and therefore the permissible total line loss is 47.2 kw, or 1.57 kw per mile of wire. Dividing the line loss per mile by the square of the assumed current gives a line resistance of

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approximately 17 ohms per mile. The constants for 0.25-in. Siemens-Martin cable at 60 cycles, 10 amp., are 12.38 ohms resistance and 0.577 ohm internal reactance per mile; the external reactance is 0.687 ohm per mile, making a total of 1.264 ohms per mile. Assuming 6% drop (2,000 volts, delta) or a delivered voltage of 31,000 at the receiver, and recalculating the problem, the line loss is found to be approximately 7.1% and the drop 5.6%. This calculation neglects the effect of the line charging current, which would be approximately 1.1 amp. per phase wire or but 12% of the load current, bringing the line loss up to possibly 8%. If a hard-drawn copper conductor were used for this line, considerations of voltage and tensile strength would require No. 4 A. W. G., which would have practically the same weight as the 0.25-in. Siemens-Martin cable but only two-thirds the strength.

Example of Applicability to Short Lines Carrying Small Loads. Given a 5-mile, 3-phase, 6,600 volt, 60 cycle line delivering 100 kw at 80% power factor with not more than 10% loss; conductor spacing, 24 in. As a first approximation, the limiting line resistance may be computed upon the basis of 8% drop. At the latter value of drop, the current necessary to deliver the load will be approximately 12 amp. The total permissible line loss is one-ninth of 100 kw or 11.1 kw. Dividing the last figure by the square of the line current gives a total effective resistance of 77.1 ohms or 5.14 ohms per mile. The conductor of nearest resistance is 0.375-in. Standard Strand. By interpolation, it will be found that this strand, at 12 amp., has an effective resistance of 4.17 ohms per mile and an effective internal reactance of 1.59 ohms per mile. The external reactance is 0.56 ohm per mile, making a total reactance of 2.15 ohms per mile. Recalculating the problem on this basis shows that the line loss will be 8.1% of the energy delivered to the line and the drop will be 7.4% of the impressed voltage, which come within the requirements. If this line should be erected at first with only two conductors (instead of three) and operated single-phase, it would deliver one-

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half as much energy, or 50 kw at 80% power factor, with the same percentage of loss and drop.

Relative Costs of steel conductors in comparison with copper or any other material may be computed with fair precision for any given set of conditions, but the variables are so numerous that general comparisons are difficult. The basis of comparison should be the total annual charges in each case, including interest, taxes, depreciation, repairs and the annual cost of supplying the line losses. Depreciation is the only factor which is open to any substantial degree of uncertainty, and is usually based upon some assumption as to useful life which seems reasonable under the circumstances of a specific case. The life of galvanized iron and steel conductors is greatly dependent upon the local atmospheric conditions, ranging anywhere from a few years in sulphurous or fog-laden atmospheres to 20 to 25 years in regions of comparatively dry climate and pure atmosphere. A reasonable assumption under conditions which do not represent either extreme is probably 15 years.

Conclusions. In selecting steel conductors for alternating-current transmission or distribution lines the choice of the harder grades of material will insure minimum skin-effect and internal reactance and maximum tensile strength. The characteristic conditions under which steel power conductors may be used with advantage can be summarized as follows:

(a) For lines of short or moderate length at very high tension, where the minimum size of conductor is fixed by corona discharge and the line resistance is a secondary consideration.

(b) For high-tension lines of short or medium length transmitting moderate amounts of energy, such that the line drop and the line loss fall within permissible limits, as for example in the case of branch or tap lines of high-tension networks.

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(c) For short lines delivering small amounts of energy at the primary voltages customary in urban and rural distribution, such that the drop and the loss are not excessive.

(d) For long or unusually severe spans requiring greater tensile strength and factor of safety than can be obtained with copper or aluminum.

Respectfully submitted,

Frank P. Fowle

Consulting Engineer

Chicago, Ill.
March 1, 1921

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APPENDIX A.

CURVES OF EFFECTIVE RESISTANCE AND INTERNAL INDUCTANCE

NOTE: These curves were plotted from the data given in the main body of the report, for each sample of conductor subjected to test.

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VARIATION OF
A. C. RESISTANCE AND
INTERNAL INDUCTANCE
OF IRON WIRES
WITH CURRENT

3/8 Inch High Strength Strand
(7 wire strand)

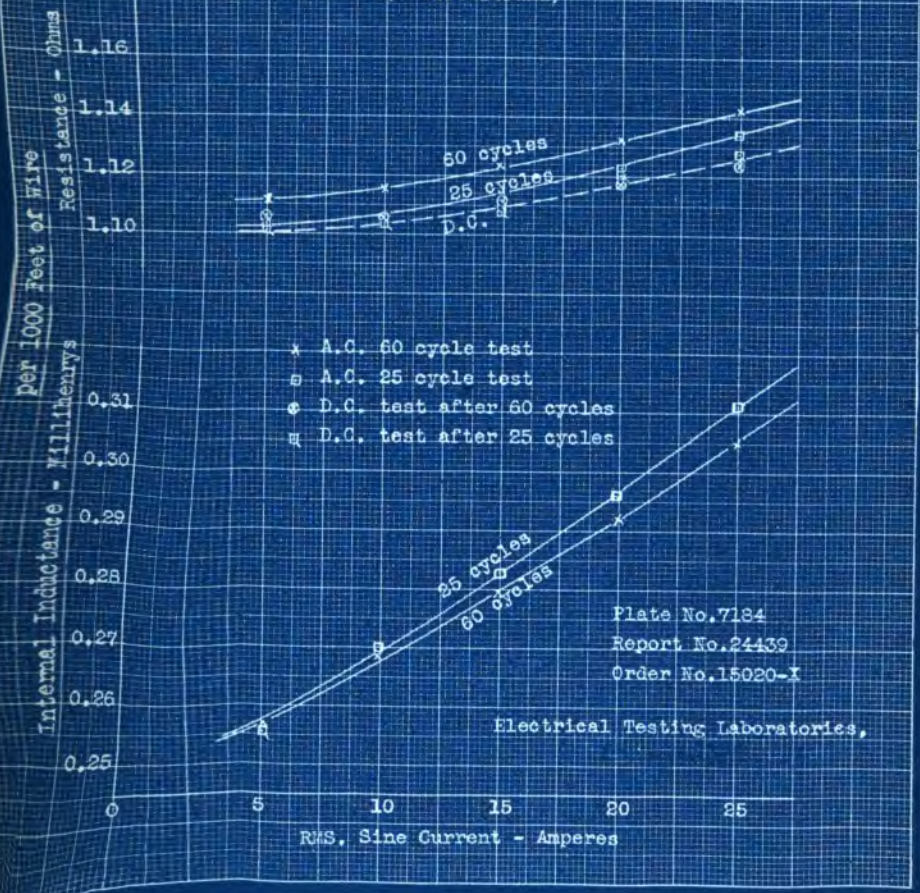

Plate No.7184
Report No.24439
Order No.15020-I

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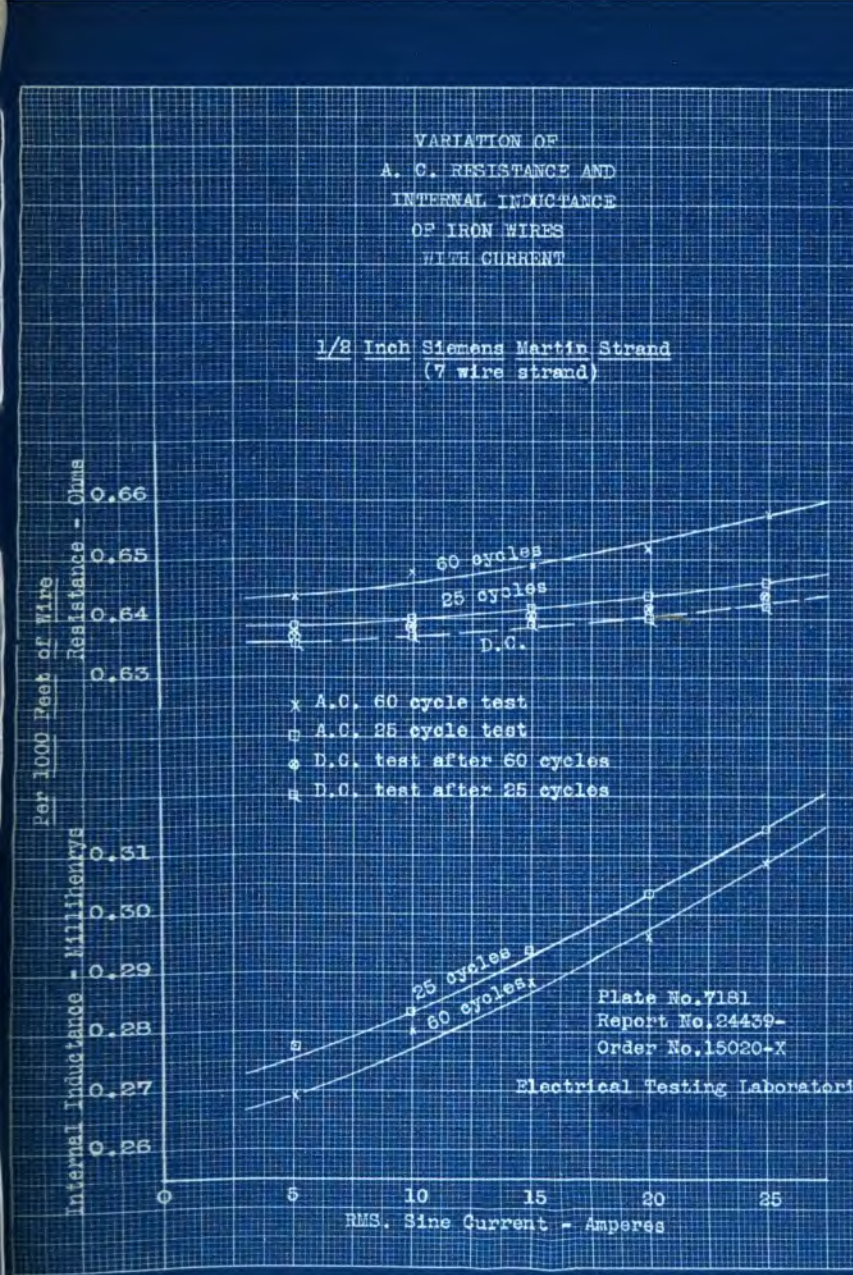
VARIATION OF
A. C. RESISTANCE AND
INTERNAL INDUCTANCE
OF IRON WIRES
WITH CURRENT

1/2 Inch Siemens Martin Strand
(7 wire strand)



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Report No.24439-
Order No.15020-X

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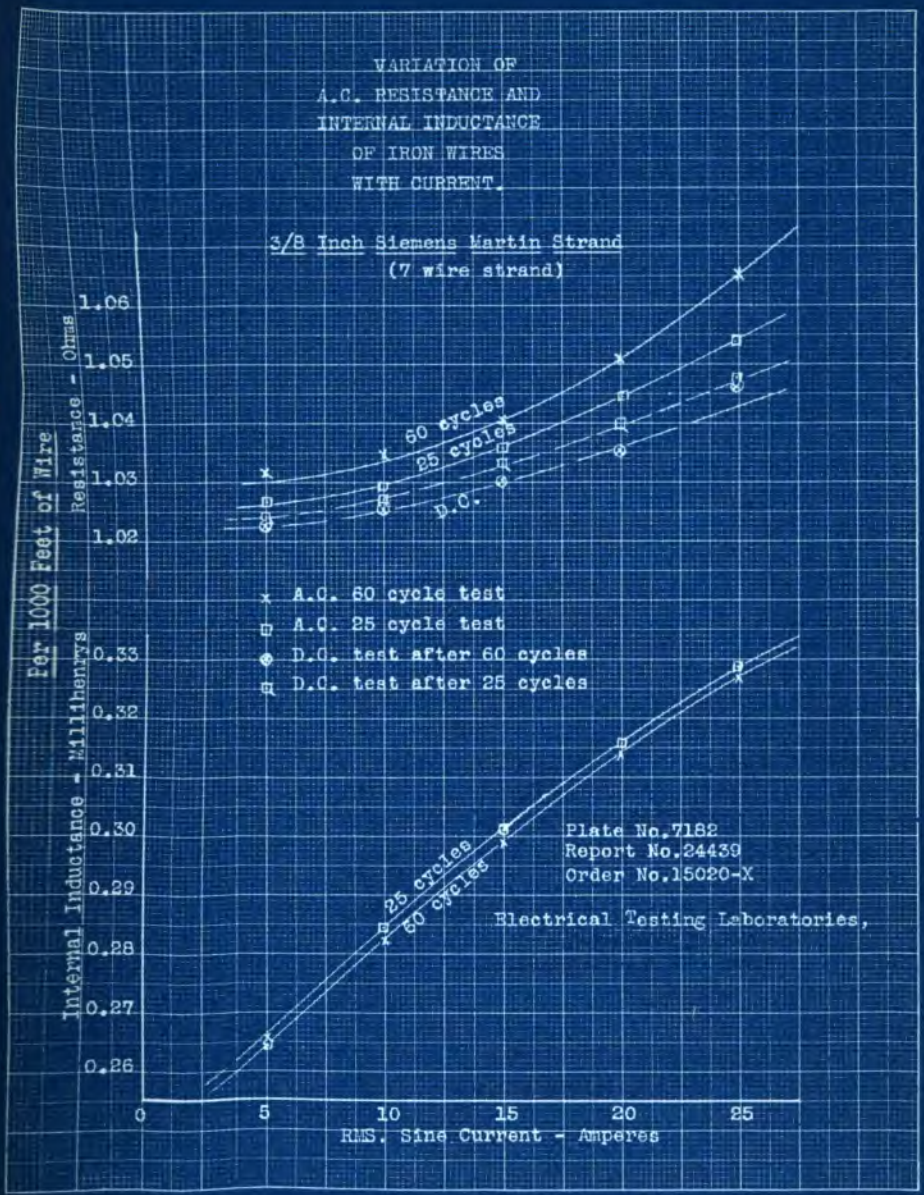

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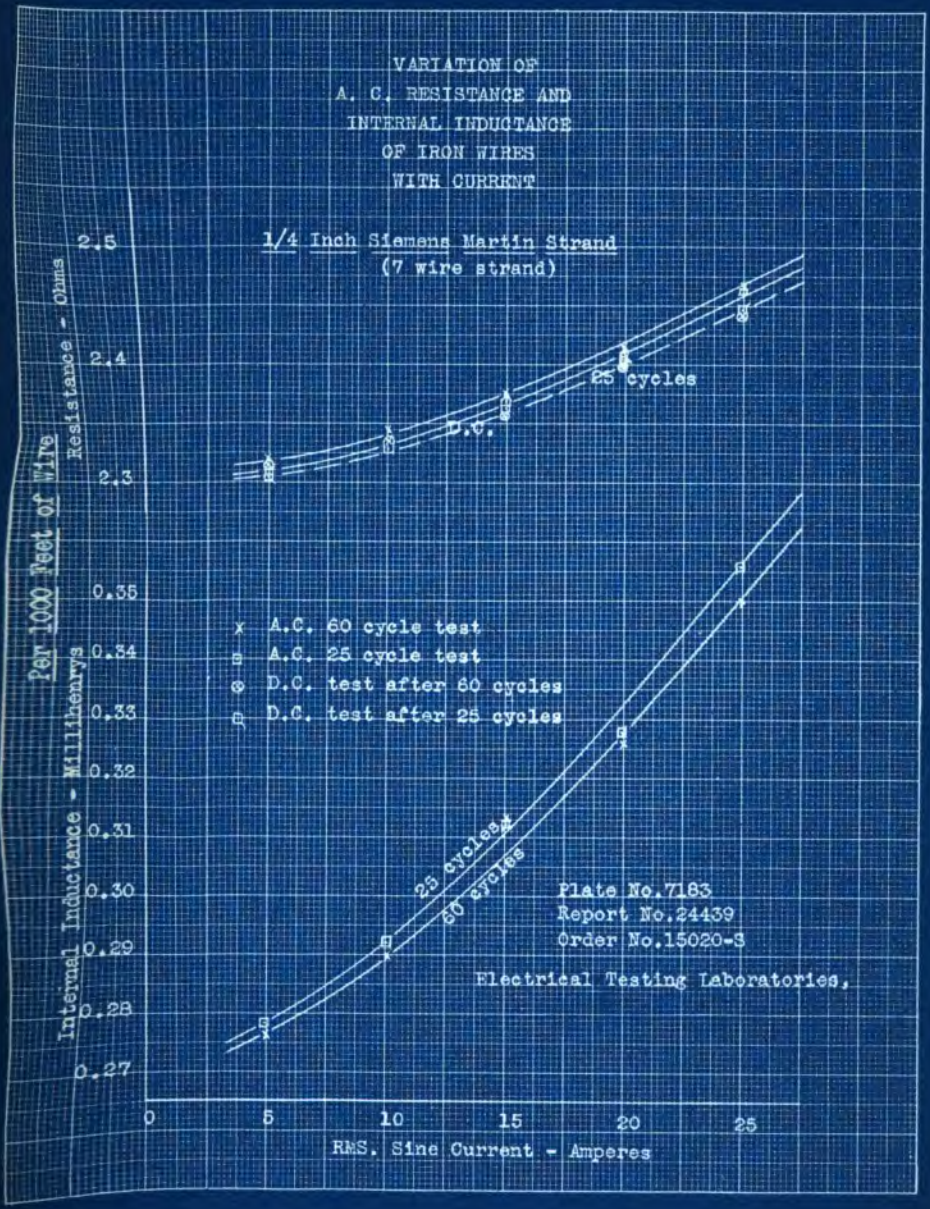

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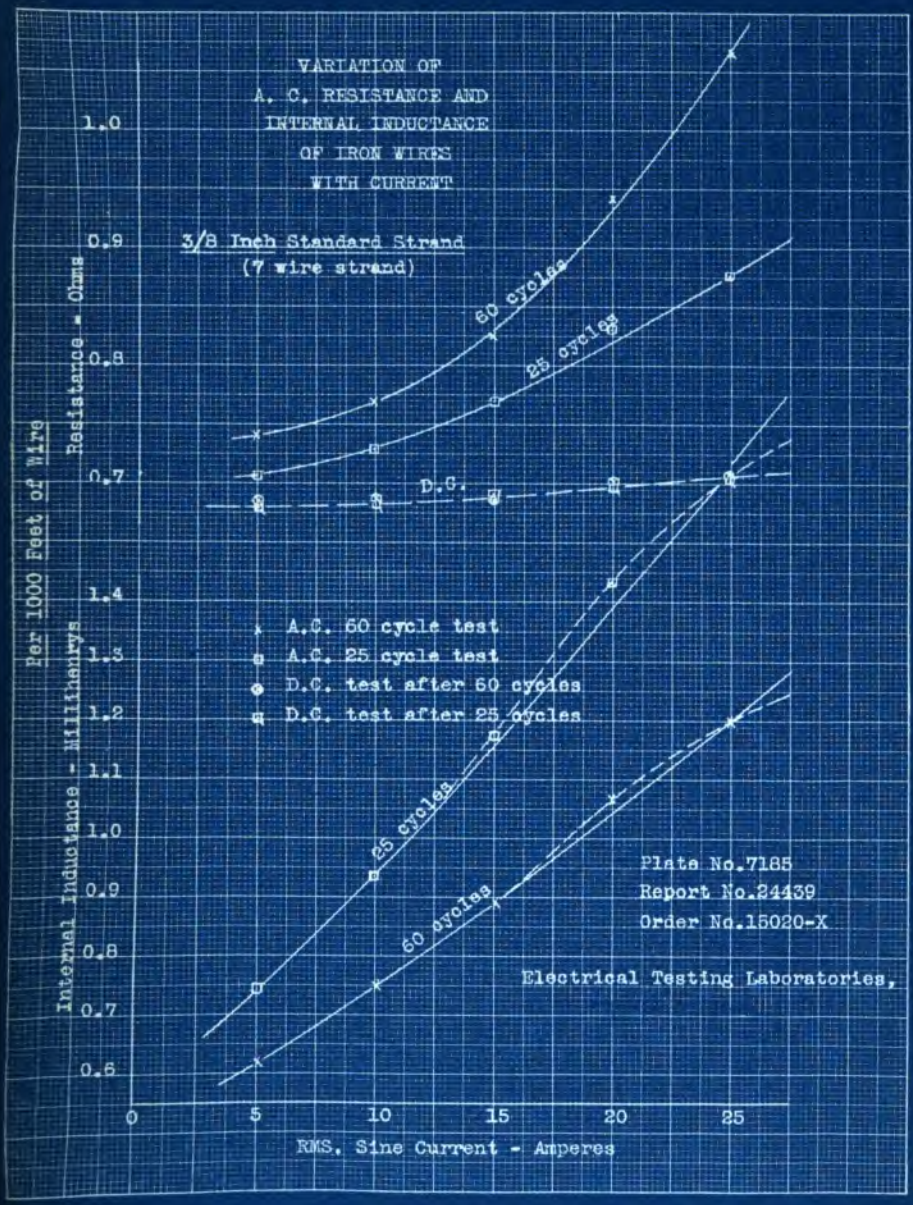

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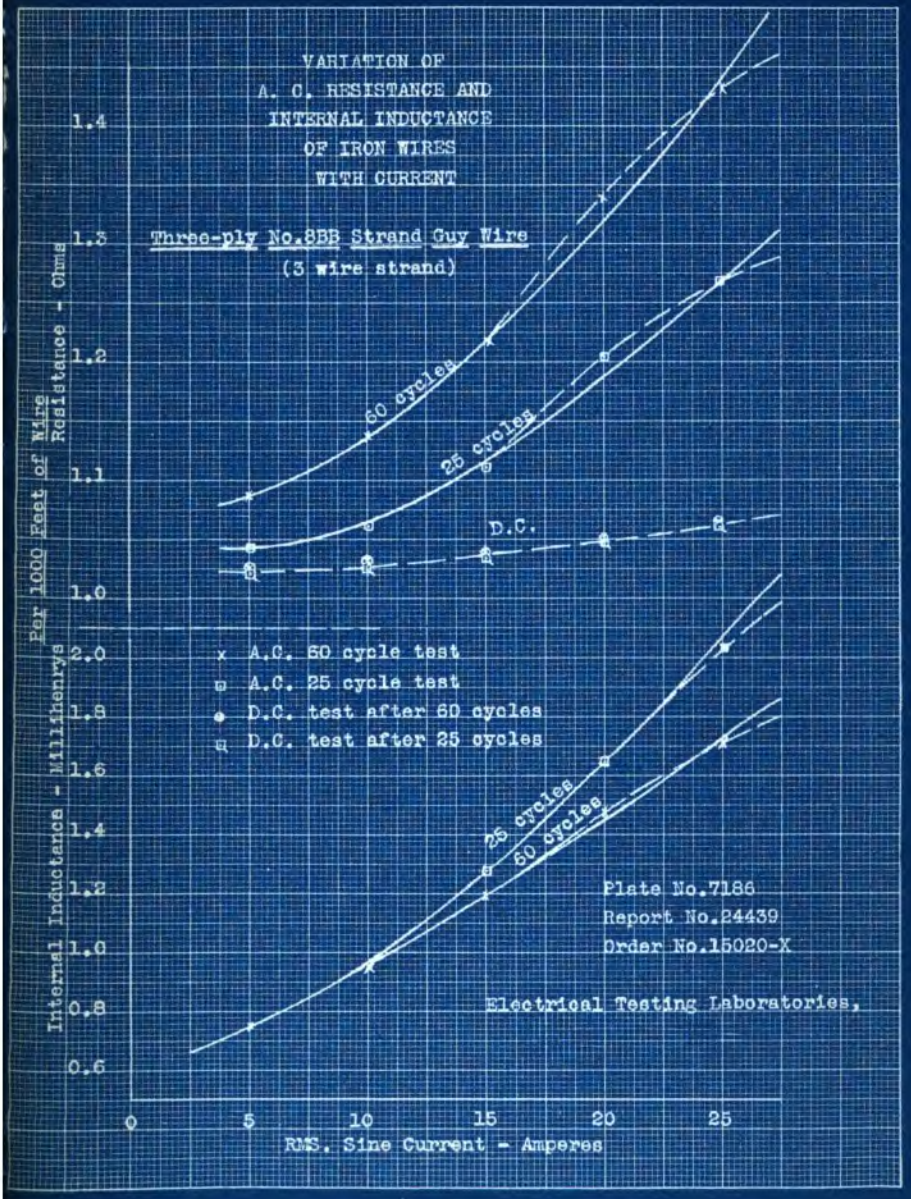

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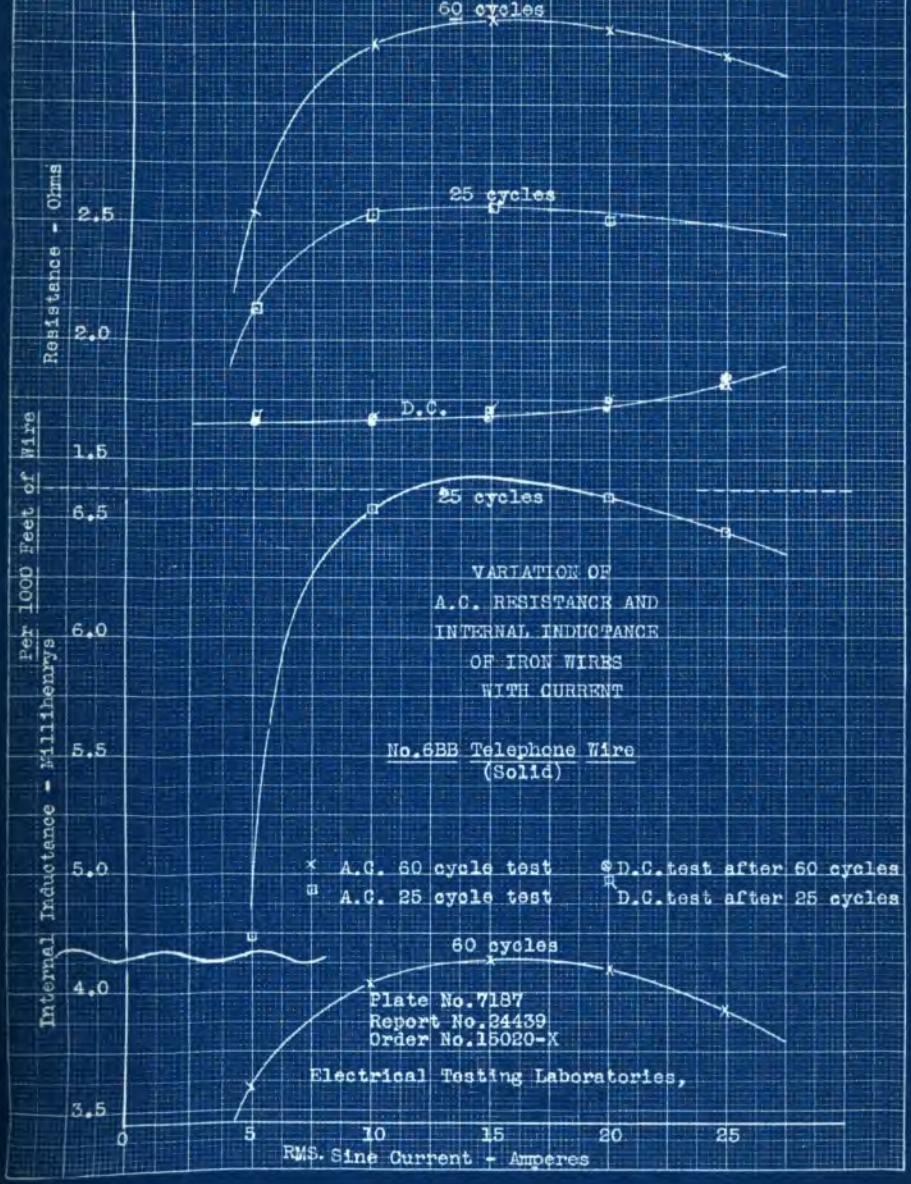

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APPENDIX B.

TABLES OF EFFECTIVE RESISTANCE, INTERNAL REACTANCE AND LINE LOSS

NOTE: These tables were prepared from the data given in the main body of the report, for each sample of conductor subjected to test.

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Resistance, Internal Reactance and Line Loss of ⅜-in. High Strength Strand

Current in Amperes	60 CYCLES			25 CYCLES		
	Ohms per Mile		Line Loss in Watts per Mile	Ohms per Mile		Line Loss in Watts per Mile
	Resistance	Internal Reactance		Resistance	Internal Reactance	
5	5.871	0.511	146.8	5.834	0.214	145.9
10	5.892	0.535	589.2	5.840	0.224	584.0
15	5.935	0.557	1335.	5.861	0.235	1319.
20	5.977	0.581	2391.	5.935	0.246	2374.
25	6.030	0.607	3769.	5.993	0.258	3746.

Resistance, Internal Reactance and Line Loss of ½-in. Siemens-Martin Strand

Current in Amperes	60 CYCLES			25 CYCLES		
	Ohms per Mile		Line Loss in Watts per Mile	Ohms per Mile		Line Loss in Watts per Mile
	Resistance	Internal Reactance		Resistance	Internal Reactance	
5	3.400	0.535	85.0	3.374	0.231	84.4
10	3.421	0.558	342.1	3.379	0.235	337.9
15	3.427	0.574	771.1	3.390	0.244	762.8
20	3.443	0.589	1377.	3.400	0.252	1360.
25	3.474	0.614	2171.	3.411	0.261	2132.

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Resistance, Internal Reactance, and Line Loss of ⅜-in. Siemens-Martin Strand.

Current in Amperes	60 CYCLES			25 CYCLES		
	Ohms per Mile		Line Loss in Watts per Mile	Ohms per Mile		Line Loss in Watts per Mile
	Resistance	Internal Reactance		Resistance	Internal Reactance	
5	5.444	0.528	136.1	5.423	0.220	135.6
10	5.465	0.561	546.5	5.433	0.236	543.3
15	5.491	0.594	1235.	5.470	0.249	1231.
20	5.549	0.623	2220.	5.512	0.261	2205.
25	5.623	0.651	3514.	5.565	0.272	3478.

Resistance, Internal Reactance and Line Loss of ¼-in. Siemens-Martin Strand.

Current in Amperes	60 CYCLES			25 CYCLES		
	Ohms per Mile		Line Loss in Watts per Mile	Ohms per Mile		Line Loss in Watts per Mile
	Resistance	Internal Reactance		Resistance	Internal Reactance	
5	12.25	0.551	306.3	12.20	0.231	305.0
10	12.38	0.577	1238.	12.30	0.242	1230.
15	12.54	0.621	2822.	12.51	0.258	2815.
20	12.75	0.649	5100.	12.72	0.272	5088.
25	13.04	0.698	8150.	13.02	0.295	8138.

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Resistance, Internal Reactance and Line Loss of ⅜-in. Standard Strand

Current in Amperes	60 CYCLES			25 CYCLES		
	Ohms per Mile		Line Loss in Watts per Mile	Ohms per Mile		Line Loss in Watts per Mile
	Resistance	Internal Reactance		Resistance	Internal Reactance	
5	3.912	1.222	97.8	3.733	0.612	93.8
10	4.071	1.479	407.1	3.844	0.773	384.4
15	4.367	1.770	982.6	4.071	0.972	916.0
20	4.979	2.124	1992.	4.382	1.189	1753.
25	5.634	2.385	3521.	4.620	1.342	2887.

Resistance, Internal Reactance and Line Loss of 3-Ply No. 8 Twisted Guy Wire

Current in Amperes	60 CYCLES			25 CYCLES		
	Ohms per Mile		Line Loss in Watts per Mile	Ohms per Mile		Line Loss in Watts per Mile
	Resistance	Internal Reactance		Resistance	Internal Reactance	
5	5.734	1.495	143.4	5.512	0.618	137.8
10	5.987	1.893	598.7	5.613	0.789	561.3
15	6.426	2.385	1446.	5.887	1.067	1325.
20	7.091	2.938	2836.	6.362	1.368	2545.
25	7.577	3.396	4736.	6.706	1.697	4191.

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Resistance, Internal Reactance and Line Loss of No. 6 B. B. Telegraph Wire

Current in Amperes	60 CYCLES			25 CYCLES		
	Ohms per Mile		Line Loss in Watts per Mile	Ohms per Mile		Line Loss in Watts per Mile
	Resistance	Internal Reactance		Resistance	Internal Reactance	
5	13.41	7.137	335.3	11.80	3.928	282.5
10	17.21	8.031	1721.	13.46	5.437	1346.
15	17.82	8.212	4010.	13.57	5.536	3053.
20	17.56	8.162	7024.	13.28	5.470	5312.
25	17.00	7.805	10630.	13.17	5.351	8233.

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APPENDIX C.

TELEPHONE TRANSMISSION EQUIVALENTS OF IRON WIRE

NOTE: The authority for the following data, here given for convenience, is the "Standard Handbook For Electrical Engineers," Fourth Edition.

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Appendix C.

Telephone Transmission Equivalents of Iron Wire

For convenience in connection with private telephone lines frequently carried on the same structures with transmission and distribution lines, the following average values of telephone transmission equivalents of iron wire are appended. These equivalents apply to iron wire of "B. B." quality when new. Transmission naturally becomes impaired as corrosion takes place and reduces the cross-section. Such corrosive action frequently makes its first appearance at the joints and for this reason the joints in iron wire should always be carefully soldered when the line is erected. Transmission equal to 30 miles of No. 19 standard cable will as a rule be quite satisfactory for private line service, assuming that the stations situated adjacent to sources of extraneous noise, as in power stations or sub-stations, are properly housed in sound-proof booths.

Material	Gage	Diameter (in.)	Miles Equivalent to one Mile of No. 19 Standard Cable	Miles Equivalent to 30 Miles of No. 19 Standard Cable
Copper	No. 9 A.W.G.	0.1144	15.6	470.
B.B. Iron	No. 8 B.W.G.	0.1650	4.5	135.
B.B. Iron	No. 10 B.W.G.	0.1340	4.0	120.
B.B. Iron	No. 12 B.W.G.	0.1090	3.1	93.
B. B. Iron	No. 14 B.W.G.	0.0830	2.5	75.

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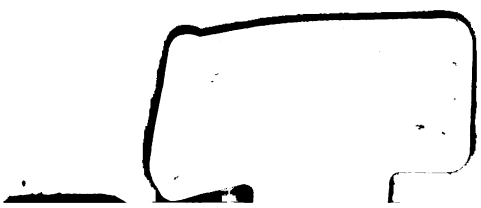

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